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On black hole masses, radio-loudness and bulge luminosities of Seyfert galaxies

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Abstract. We estimated black hole masses for 9 Seyfert 1 and 13 Seyfert 2 galaxies in Palomar and CfA bright Seyfert samples using the tight correlation between black hole mass and bulge velocity dispersion. Combining other 13 Seyfert 1s and 2 Seyfert 2s in these samples but with black hole masses measured recently by reverberation mapping and stellar/gas dynamics, we studied the correlations of black hole masses with radio loudness and bulge luminosities for a sample of 37 Seyfert galaxies. We found that if radio-loudness is measured using the optical and radio luminosities of the nuclear components, the black hole masses of radio-loud Seyfert 1s tend to increase with the radio-loudness. The black hole masses of all Seyfert galaxies increase with the radio power, but Seyfert galaxies have larger radio powers than nearby galaxies with the same black hole masses. In addition, the correlation between black hole masses and bulge V-band luminosities for Seyfert galaxies is consistent with that found for quasars and normal galaxies. The combined sample of 37 Seyfert galaxies, 15 quasars and 30 normal galaxies suggests a possible universal nonlinear relation between black hole and bulge masses, $M_{BH} \propto M_{bulge}^{1.74\pm0.14}$, which is slightly steeper than that found recently by Laor (2001) for a smaller sample. This nonlinear relation is supported by a larger sample including 65 Seyfert galaxies. The different M_{BH}/M_{bulge} ratio for galaxies with different bulge luminosities or different black hole masses may be explained by this relation. These results are consistent with some theoretical implications and are important for understanding the nature of radio emissions and the formation and evolution of supermassive black holes and galaxies.

Key words. black hole physics – galaxies: active – galaxies: nuclei – galaxies: Seyfert

1. Introduction

Supermassive black holes (SMBHs), with masses in the range of 10^6 to $10^9 M_\odot$, have been suggested to exist in the center of quasars and active galactic nuclei (AGNs). Accretion onto these SMBHs may account for the huge power of these energetic objects (Lynden-Bell 1969; Rees 1984). Recently, the masses of central objects in 20 Seyfert galaxies and 17 nearby quasars have been measured with the reverberation mapping technique (Ho 1999; Wandel, Peterson & Malkan 1999; Kaspi et al. 2000), which confirmed the existence of SMBHs in the center of these objects. On the other hand, a lot of observations using gas and stellar dynamics indicated that SMBHs probably also exist in the center of our Galaxy (Ghez et al. 1998; Genzel et al. 1997) and in the nuclei of many normal galaxies (Kormendy & Richstone 1995; Magorrian et al. 1998; Kormendy & Gebhardt 2001). However, the apparent inactive feature of normal galaxies seems to suggest that the central engines of these galaxies may be different from those in quasars and AGNs. It was suspected that advection-dominated accretion flows (ADAFs; see Narayan, Mahadevan & Quataert 1998 and Kato, Fukue & Mineshige 1998 for reviews) with very low accretion rate and low radiative efficiency may exist in the nuclei of normal galaxies (Fabian & Rees 1995; Di Matteo & Fabian 1996), while quasars and most AGNs probably host the standard geometrically thin accretion disks (Shakura & Sunyaev 1973; Novikov & Throne 1973) with higher accretion rate.

One interesting result found recently in the searches of SMBHs in nearby galaxies is the correlation of black hole masses with the properties of galactic bulges. Although with large scatters, the black hole masses seem to correlate with bulge luminosities (Kormendy 1993; Kormendy & Richstone 1995; Magorrian et al. 1998). This also leads to the finding that the black hole mass, M_{BH}, is possibly proportional to the bulge mass, M_{bulge}, though the mass ratio found by different authors was different, in the range of 0.2% to 0.6% (Kormendy & Richstone 1995; Magorrian et al. 1998; Ho 1999). Laor (1998; 2001) recently found

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that some nearby quasars and Seyfert galaxies follow nearly the same M_{BH}-bulge luminosity relation as normal galaxies, and suggested a universal nonlinear relation, $M_{BH} \propto M_{bulge}^{1.54\pm0.15}$, for both normal and active galaxies. This means that the M_{BH}/M_{bulge} ratio is not constant for galaxies with different bulge luminosities. Recently, a significantly tight correlation of M_{BH} with the bulge velocity dispersion σ was also found for nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000). More recent studies indicated that 11 Seyfert galaxies with M_{BH} measured by reverberation mapping follow the same M_{BH}-σ relation as for normal galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), implying another possible universal relation for both normal and active galaxies. The correlations of the SMBH mass with the properties of the galactic bulge strongly suggest a tight connection between the formation and evolution of the SMBH and galactic bulge, though the nature of this connection is still in debate (Haehnelt & Rees 1993; Haiman & Loeb 1998; Silk & Rees 1998; Haehnelt, Natarajan & Rees 1998; Kauffmann & Haehnelt 2000; Adams, Graff & Richstone 2001)

Nonthermal radio emissions of quasars and AGNs are believed to be probably produced by relativistic electrons that are powered by jets (Begelman, Blandford & Rees 1984; Blundel & Beasley 1998). Similar radio emissions have been detected in the nuclei of normal elliptical galaxies (Sadler, Jenkins & Kotanyi 1989) and also in some spiral galaxies (Sadler et al. 1995). Recently, some studies have indicated that the radio power may be directly correlated with the black hole mass. Franceschini, Vercellone & Fabian (1998) found a very tight relation between black hole mass and radio power in a small sample of nearby mostly non-active galaxies. McLure et al. (1999) estimated the black hole masses for a sample of AGNs using M_{BH}-bulge mass relation found by Magorrian et al. (1998) and noted they follow the same correlation with radio power as found by Franceschini et al. (1998). However, Laor (2000) recently argued that the M_{BH} and radio power of a sample of 87 $z < 0.5$ Palomar-Green (PG) quasars (Schmidt & Green 1983; Boroson & Green 1992) do not follow the tight correlation suggested by Franceschini et al. (1998), because quasars usually have over 100 times larger radio power than normal galaxies at a given M_{BH}. He suggested that the larger scatters of radio power at a given M_{BH} may be simply due to the different levels of overall continuum luminosity of different objects. Laor (2000) also noted that the radio-loud quasars seem to host more massive black holes than radio-quiet quasars. Very recently, Ho & Peng (2001) studied the radio-loudness of bright Seyfert 1 galaxies using the nuclear radio and optical luminosities, and suggested that the majority of Seyfert 1 nuclei in their sample are essentially radio loud. Therefore, it is useful and feasible to check if these radio-loud Seyfert nuclei host more massive black holes than radio-quiet ones and if the Seyfert galaxies still follow the same correlation between the radio power and black hole masses of nearby galaxies and quasars (Franceschini et al. 1998; Laor 2000). In this paper we will try to derive the SMBH masses for a number of Seyfert galaxies and study their correlations with radio power and bulge luminosities. Further studies of these correlations will probably provide some important clues to help us understand the nature of radio emissions in active and normal galaxies and the formation and evolution of SMBHs and galaxies.

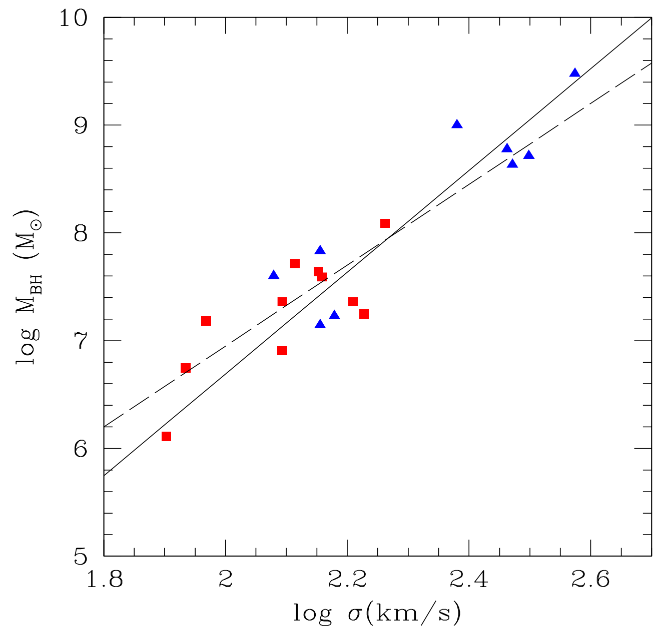

Fig. 1. The black hole mass (in $M_\odot$) against the velocity dispersion for Seyfert galaxies. Squares and triangles represent the SMBH masses measured by reverberation mapping and stellar/gas dynamics, respectively. The solid and dashed lines correspond to the correlation found by Merritt & Ferrarese (2000) and Gebhardt et al. (2000a), respectively.

2. Estimating the SMBH masses of Seyfert galaxies

Currently the SMBH masses of a few weak AGNs have been well measured by stellar dynamics, ionized gas dynamics and water maser dynamics (for a summary see Table 1s in Ho 1999 and Gebhardt et al. 2000a). Using the reverberation mapping technique, the SMBH masses of 20 Seyfert galaxies and 17 bright quasars have been recently estimated (Ho 1999; Wandel et al. 1999; Kaspi et al. 2000). However, for most Seyfert galaxies, it is difficult to measure the SMBH mass using these methods because of either the large nuclear luminosity or the lack of long-term variability monitoring and precise measurements of characteristic velocity dispersions in the broad emission line region.

Since the tight correlation between the SMBH mass and bulge velocity dispersion was found for both normal and active galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001), it may be straightforward to estimate the

SMBH mass from the measured bulge velocity dispersion. The correlation between the black hole mass and nuclear velocity dispersion for Seyfert galaxies with both measured nuclear velocity dispersions and black hole masses is demonstrated in Figure 1. The SMBH masses of 11 Seyfert galaxies (squares in Figure 1) were estimated by reverberation mapping (Wandel et al. 1999) and 9 (triangles in Figure 1) by the dynamical method (Ho 1999; Gebhardt et al. 2000a). The values of their central velocity dispersions were taken from Nelson & Whittle (1995) and Ferrarese et al. (2001). Figure 1 clearly shows that Seyfert galaxies follow the same M_{BH}-σ relation as normal galaxies (Gebhardt et al. 2000a; Merritt & Ferrarese 2000). Although measurements of the central velocity dispersions of these Seyfert galaxies were made by different groups, the small scattering around the M_{BH}-σ relation indicates that these measurements were reliable and the systematic errors may not be important (Ferrarese et al. 2001). In this paper, we adopt the M_{BH}-σ relation found by Merritt & Ferrarese (2001), namely,

$$M_{BH} = 1.3 \times 10^8 M_\odot (\sigma/200 \text{ km s}^{-1})^{4.72}, \qquad (1)$$

to derive the SMBH masses for Seyfert galaxies with measured nuclear velocity dispersions. Using a slightly flatter relation found by Gebhardt et al. (2000) does not cause significant changes in our results.

In the next sections we will compare some properties of Seyfert galaxies with those of quasars. Only a few quasars have SMBH masses determined by reverberation mapping. Laor (1998) adopted an empirical relation between the size of the broad line region (BLR) and the bolometric luminosity, $R_{BLR} \propto L^{1/2}$ (Kaspi et al. 1996; see also Kaspi et al. 2000 for a slightly steeper relation), and derived the SMBH mass for a number of quasars using the measured $H\beta$ velocity dispersion and the continuum luminosity. We have compared the estimated SMBH masses for 9 Seyfert galaxies using Laor's method (but adopted the BLR velocity $V = (\sqrt{3}/2)$FWHM(Hβ), as did Kaspi et al. (2000)) with the those obtained by reverberation mapping, and found that they agree well. This shows that using SMBH masses derived with different methods may not cause serious problems in our present work.

3. Sample of Seyfert galaxies

We selected 37 Seyfert galaxies from two well-studied nearby Seyfert samples, the Palomar optical spectroscopic survey of bright ($B_T \leq 12.5$mag), northern ($\delta > 0^o$) galaxies (Ho, Filippenko & Sargent 1995), including 21 Seyfert 1s and 28 Seyfert 2s (Ho et al. 1997a), the most complete and least biased available (Ho, Filippenko & Sargent 1997b; Ho & Ulvestad 2001), and the CfA redshift Survey (Huchra et al. 1983) of galaxies with Zwicky magnitude ≤ 14.5, including 33 Seyfert 1s and 15 Seyfert 2s (Huchra & Burg 1992; Osterbrock & Martel 1993). The Seyfert samples from these two surveys seem to complement one another, though the combined sample may not be complete (Ho & Peng 2001).

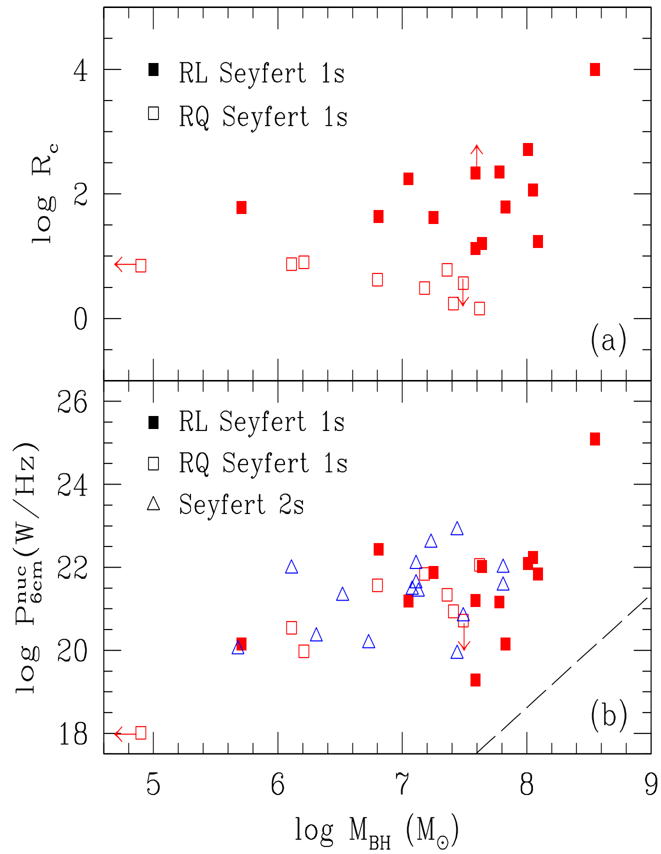

Fig. 2. The nuclear radio-loudness and the nuclear radio power against the black hole masses for Seyfert galaxies. The dashed line in the lower panel represents the tight correlation between the core radio power and the SMBH masses for nearby galaxies found by Franceschini et al. (1998).

Our Seyfert sample include 22 Seyfert 1s and 15 Seyfert 2s in Palomar and CfA samples (see Table 1). These Seyfert galaxies have either the measured SMBH masses or the measured central velocity dispersions. Among them, three Seyfert 1s and two Seyfert 2s have dynamical SMBH masses (Ho 1999; Gebhardt et al. 2000a), and ten Seyfert 1s have SMBH masses measured by the reverberation mapping method (Wandel et al. 1999; Ho 1999). Another Nine Seyfert 1s and 13 Seyfert 2s have measured central velocity dispersions but unknown SMBH masses (Nelson & Whittle 1995). The SMBH masses can be estimated by equation (1) using the measured central velocity dispersions. Therefore, our sample consists of 37 Seyfert galaxies with derived SMBH masses (see Table 1).

4. Radio properties and black hole masses of Seyfert galaxies

The radio properties of Seyfert galaxies have been investigated in detail using the Very Large Array (VLA) at 3.6 cm by Kukula et al. (1995) for the CfA sample, and at 6

Table 1. Black hole mass of a sample of Seyfert 1 and Seyfert 2 galaxies

Name	Type	M_B^{tot}	B-V	M_B^{nuc}	$\log P_{6cm}^{nuc}$ (W/Hz)	$\log R_c$	M_B^{bul}	M_{BH} ($10^7 M_\odot$)	Note*
Mrk 279	Sy1	-20.92	0.69	-20.55	22.06	0.16	-20.31	4.2 ± 1.7	C,1,a
Mrk 335	Sy1	-21.48	0.34	-18.18	21.57	0.62	-20.62	$0.63^{+0.23}_{-0.17}$	C,1
Mrk 590	Sy1	-21.42	0.67	-16.46	21.88	1.62	-20.40	$1.78^{+0.44}_{-0.33}$	C,1
Mrk 817	Sy1	-21.03	0.40	-17.81	22.02	1.21	-18.49	$4.4^{+1.3}_{-1.1}$	C,1
NGC 3227	Sy1	-20.57	0.82	-16.01	21.20	1.12	-19.55	$3.9^{+2.1}_{-3.9}$	P,C,1
NGC 3516	Sy1	-20.63	0.72	-17.21	21.34	0.78	-20.02	2.3 ± 0.9	P,C,1,a
NGC 4051	Sy1	-20.38	0.67	-14.97	20.54	0.87	-18.41	$0.13^{+0.13}_{-0.08}$	P,C,1
NGC 4151	Sy1	-20.16	0.71	-19.18	21.84	0.49	-18.93	$1.53^{+1.06}_{-0.89}$	P,C,1
NGC 5548	Sy1	-20.97	0.62	-17.29	21.84	1.24	-20.11	$12.3^{+2.3}_{-1.8}$	P,C,1
NGC 7469	Sy1	-21.32	0.38	-17.78	22.43	1.64	-20.30	$0.65^{+0.64}_{-0.65}$	C,1
NGC 3031	Sy1	-20.24	1.12	-11.73	20.16	1.79	-19.01	$0.68^{+0.07}_{-0.13}$	P,2
NGC 4258	Sy1	-20.13	0.77	>-8.17	19.29	>2.34	-18.16	0.39 ± 0.034	P,2
NGC 4395	Sy1	-16.51	0.53	-8.69	18.01	0.85	>-16.51	<0.008	P,C,2
Mrk 530	Sy1	-21.48	0.72	-16.27	22.24	2.06	-19.94	11.26 ± 8.49	C,3
Mrk 744	Sy1	-19.96	0.88	-17.56	20.94	0.24	-18.94	2.58 ± 1.11	C,3
NGC 1275	Sy1	-22.29	0.62	-18.53	25.09	4.00	>-22.29	35.88 ± 11.61	P,3
NGC 3982	Sy1	-19.43	0.80	-11.76	20.16	1.78	-17.89	0.052 ± 0.047	P,3,b
NGC 4388	Sy1	-19.51	0.80	-13.17	21.19	2.24	-17.97	1.12 ± 0.80	P,3,d
NGC 4579	Sy1	-20.82	0.97	-12.81	21.16	2.35	-19.28	6.04 ± 3.02	P,3
NGC 5252	Sy1	-20.93	1.00	-14.23	22.10	2.72	-20.32	10.20 ± 6.84	C,3
NGC 5273	Sy1	-19.24	0.89	-13.51	19.98	0.90	-18.63	0.16 ± 0.08	P,C,3
NGC 6104	Sy1	-21.12	0.80	-16.17	<20.72	<0.57	-20.10	$3.14^{+3.50}_{-3.14}$	C,3,b
NGC 3079	Sy2	-21.14	0.87	...	21.97	...	-16.91	1.3 ± 0.4	P,2
NGC 1068	Sy2	-21.32	0.87	...	22.59	...	-19.78	$1.7^{+1.3}_{-0.7}$	P,C,2
NGC 1358	Sy2	-20.95	1.05	...	21.56	...	-20.09	6.56 ± 2.50	P,3
NGC 1667	Sy2	-21.52	0.80	...	21.99	...	-18.98	6.56 ± 4.65	P,3,d
NGC 2273	Sy2	-20.25	0.78	...	21.41	...	-19.32	1.36 ± 0.52	P,3
NGC 3185	Sy2	-18.99	0.80	...	20.02	...	-17.97	$0.048^{+0.074}_{-0.048}$	P,3
NGC 5194	Sy2	-20.76	0.91	...	20.17	...	-18.79	$0.54^{+0.63}_{-0.54}$	P,3
NGC 7743	Sy2	-19.78	0.91	...	20.33	...	-19.05	$0.20^{+0.23}_{-0.20}$	P,3
Mrk 573	Sy2	-20.32	0.83	...	21.61	...	-19.71	1.31 ± 0.80	C,3
NGC 3362	Sy2	-21.99	0.80	...	21.31	...	-19.45	$0.33^{+0.48}_{-0.32}$	C,3,b
NGC 5929	Sy2	-20.48	0.80	...	21.46	...	-19.24	1.21 ± 0.62	C,2,b
NGC 7682	Sy2	-20.23	0.80	...	22.08	...	-19.00	1.31 ± 0.85	C,3,b
NGC 5283	Sy2	-19.40	0.92	...	20.82	...	-18.79	3.14 ± 1.40	C,3
NGC 5695	Sy2	-20.50	0.95	...	19.91	...	-19.48	2.76 ± 0.99	C,3
NGC 7674	Sy2	-21.77	0.83	...	22.89	...	-19.81	$2.76^{+2.89}_{-2.76}$	C,3

*Notes: (C), object in CfA Seyfert sample; (P), object in Palomar Seyfert sample; (1), M_{BH} measured by reverberation mapping; (2), M_{BH} measured by gas/stellar dynamics; (3), M_{BH} obtained in this paper using the M_{BH}–σ relation; (a), uncertainty of M_{BH} not available in literature and assumed to be 40%; (b), B-V value not available in literature and assumed to be 0.80; (d), uncertainty of σ not available in literature and assumed to be 15%.

cm and 20 cm recently by Ho & Ulvestad (2001) for the Palomar sample. In this paper, we adopt the radio data for Seyfert 1s from Ho & Peng (2001) and the data for Seyfert 2s from Ho & Ulvestad (2001) and Kukula et al. (1995). The 6 cm data for some sources in the CfA sample (Kukula et al. 1995) were extrapolated from the 3.6cm data assuming $f_\nu \propto \nu^{-0.5}$.

Seyfert galaxies have been considered usually as radio-quiet AGNs because most of them have lower radio-loudness, defined as the ratio of the radio to optical luminosities, $R = L_{6cm}/L_B$. However, a recently study of Ho & Peng (2001) showed that though the nuclear radio power for Seyfert 1 galaxies on average accounts for about 75% of the total radio emission, the nuclear optical luminosity, measured by high-resolution optical images, accounts for merely 0.01% of the integrated light. If the radio-loudness is measured by the nuclear radio and optical luminosities, most Seyfert 1s are in the category of radio-loud AGNs (with radio-loudness larger than 10). In Table 1, we listed the total and nuclear absolute B magnitudes ($M_B^{\rm tot}$ and $M_B^{\rm nuc}$) and nuclear radio power (P_{6cm}) for Seyfert galaxies. The nuclear radio-loudness, R_c, is calculated by $R_c = L_{6cm}^{\rm nuc}/L_B^{\rm nuc}$. The Hubble constant $H_0 = 75 {\rm kms^{-1}Mpc^{-1}}$ and the deceleration parameter of $q_0 = 0.5$ were adopted. For Seyfert 2s, the measurements of their nuclear optical magnitudes are not available in the literature.

Figure 2 shows the relation of SMBH masses with the nuclear radio-loudness of Seyfert 1s and the radio power of Seyfert galaxies listed in Table 1. It is clear that the radio-

loud Seyfert 1s with larger nuclear radio-loudness seem to host more massive black holes. The similar tendency has been found for PG quasars by Laor (2000). From Figure 2(b) we see a trend that Seyfert galaxies having a larger radio power perhaps host a more massive black hole than those of less radio power. With the same black hole mass, Seyfert galaxies seem to have 100 to 1000 times greater radio power than normal galaxies. Laor (2000) has shown that PG quasars also depart from such a correlation for nearby galaxies, with the radio luminosity of quasars being 10^4 larger at a given M_{BH}. The difference of radio luminosities of quasars, Seyfert galaxies and nearby galaxies may be simply due to different levels of nuclear activity.

5. Black hole masses and bulge luminosities

The correlation of black hole mass and galactic bulge luminosity found for nearby galaxies implies a relationship between the black hole and bulge masses (Kormendy & Richstone 1995; Magorrian et al. 1998; Ho 1999). However, it is not clear whether the ratio between black hole and bulge masses remains constant for all kinds of objects. Laor (2001) recently checked the correlation between the estimated black masses and bulge luminosities for 15 nearby quasars and 9 Seyfert galaxies, and found that they probably follow the same M_{BH}-bulge luminosity relation as for 16 nearby galaxies. This suggests a universal nonlinear relation between the estimated black masses and bulge luminosities, $M_{BH} \propto M_{bulge}^{1.54\pm0.15}$, for both normal and active galaxies. Therefore, M_{BH}/M_{bulge} ratio is not constant for galaxies with different bulge luminosities. However, this needs to be confirmed by larger samples including both normal and active galaxies.

5.1. Our sample of Seyfert galaxies

We use the 37 Seyfert galaxies with derived SMBH masses in our sample to check the M_{BH}/M_{bulge} ratio. The absolute total B magnitudes (M_B^{tot}) for our Seyfert sample (see Table 1) were taken from Ho et al. (1997b) and Whittle (1992) (adapted to $H_0 = 75 \mathrm{kms^{-1}Mpc^{-1}}$). The absolute bulge B magnitudes (M_B^{bulge}) were obtained based on the relation between M_B^{bulge} and M_B^{tot} (Simien & de Vaucouleurs 1986) and the Hubble stages (defined in de Vaucouleurs, de Vaucouleurs & Corwin 1976) of the host galaxies. The B-V colors were taken from Verón-Cettty & Verón (2000). In order to compare our result with those obtained for quasars and nearby galaxies, we convert M_B^{bulge} of Seyfert galaxies to the absolute bulge V magnitude, M_V^{bulge} (adapted to $H_0 = 80 \mathrm{kms^{-1}Mpc^{-1}}$) by assuming that B-V color in the bulge is nearly the same as the total B-V color of Seyfert galaxy. In Figure 3 we show the relation between the SMBH masses and bulge V-band absolute magnitudes for Seyfert galaxies and the comparison of this relation with those for quasars and nearby galaxies. The SMBH masses of 15 quasars and the absolute V magnitudes of their inner host were taken from Laor

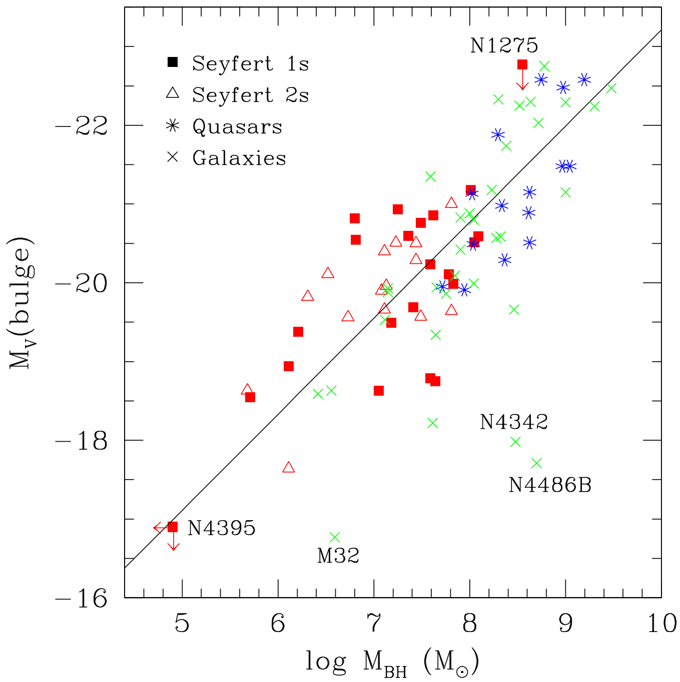

Fig. 3. Correlation of V-band bulge absolute magnitudes and SMBH masses for Seyfert galaxies, quasars and normal galaxies. The solid line represents the least χ^2 fit to all objects by considering typical measurement errors of both parameters.

(1998, 2001).[1] The SMBH masses determined by stellar and gas dynamics for 33 nearby galaxies were taken from Kormendy & Gebhardt (2001) (we omitted M 81, a Seyfert 1 already in our Seyfert sample, and 3 objects with black hole masses measured by maser dynamics). Their absolute bulge V magnitudes were derived from B-band absolute bulge magnitudes by adopting a standard bulge color, B-V = 0.94 (Worthey 1994). It is evident that both Seyfert and nearby galaxies, as well as quasars, seem to follow the same M_V^{bulge}-M_{BH} relation. Note that unlike others, nearby galaxies NGC 4342, NGC 4486B and M 32 deviate significantly from the M_V^{bulge}-M_{BH} relation. These offset galaxies are usually fainter because the outer regions of them may have been stripped away in the tidal interactions with more massive companions (Faber 1973). These three galaxies, together with two Seyfert 1 galaxies, NGC 1275 with peculiar Hubble type and NGC 4395 with only the upper limit of measured SMBH mass, are not included in our statistical studies. The measurement errors of $M_{BH}/M_\odot$ of our Seyfert sample were listed in Table 1, and those of normal galaxies were adopted from Kormendy & Gebhardt (2001). For nearby quasars, such errors are not available in Laor (1998) and assumed to be 60%. The measurement errors of M_V^{bulge} were seldom men-

[1] Because we used BLR velocity dispersion as $V = (\sqrt{3}/2)\mathrm{FWHM(H\beta)}$, the SMBH masses of 15 quasars are smaller by a factor of 0.75 than those given by Laor (1998).

tioned in the literature and thus are difficult to estimate. These errors for Seyfert galaxies were allocated to be 0.5, 0.75 and 1.0 mag respectively based on their quality assessment factors (Whittle 1992). Those of normal galaxies and nearby quasars were adopted to be 0.5 and 0.75 mag, respectively. Taking into account these 'typical' errors of M_V^{bulge} and M_{BH}, the least χ^2 fit for 35 Seyfert galaxies, 15 quasars and 30 normal galaxies gives:

$$M_V^{bulge} = -11.01 \pm 0.78 - (1.22 \pm 0.10)\log(M_{BH}/M_\odot). \quad (2)$$

The Spearman rank-order correlation coefficient is $r_S = -0.76$, which has a probability of $P_r = 3.3 \times 10^{-16}$ occurring by chance. Considering the errors in both parameters, we adopted a bootstrap method to estimate the uncertainty of this correlation, and obtained the mean correlation coefficient $\langle r_S \rangle = -0.63 \pm 0.05$. Using the standard relation

$$M_V^{bulge} = 4.83 - 2.5\log L_{bulge}/L_\odot, \quad (3)$$

and the relation between the bulge mass and luminosity (Magorrian et al. 1998),

$$\log(M_{bulge}/M_\odot) = -1.11 + 1.18\log(L_{bulge}/L_\odot), \quad (4)$$

we then can get from eq. (2),

$$\log(M_{BH}/M_{bulge}) = -11.06 \pm 1.11 + (0.74 \pm 0.14) \log(M_{bulge}/M_\odot). \quad (5)$$

This gives $M_{BH} \propto M_{bulge}^{1.74\pm0.14}$. The fitting for a sample of 35 Seyfert galaxies and 30 normal galaxies alone gives almost identical results. Laor (2001) recently found $M_{BH} \propto M_{bulge}^{1.54\pm0.15}$ for a sample of objects including 9 Seyfert galaxies and 15 quasars. Our result shows that this nonlinear relation is more evident from a larger sample including more Seyfert galaxies. Eq. (5) also shows that M_{BH}/M_{bulge} is about 0.02 when $M_{BH} = 10^6 M_\odot$, and is 0.3% when $M_{BH} = 10^9 M_\odot$. This clearly indicates that galaxies with more massive black holes have a larger M_{BH}/M_{bulge} ratio.

5.2. Seyfert sample in reverberation mapping studies

We noted that the above universal M_V^{bulge}-M_{BH} relation (eq. 2) is contrary to the result obtained by Wandel (1999), who found that Seyfert 1 galaxies significantly depart from the L_{bulge}-M_{BH} relations of quasars and nearby galaxies (Laor 1998; Magorrian et al. 1998). However, Mclure & Dunlop (2001) used the decomposed bulge luminosities of the same sample of Seyfert galaxies as in Wandel (1999) and found no evidence for a different L_{bulge}-M_{BH} relation from quasars. We noted that Wandel (1999) took the absolute bulge B magnitude, M_B^{bulge}, for Seyfert galaxies from Whittle (1992)(adopting $H_0 = 50$kms^{-1}Mpc^{-1}) and calculated the bulge luminosity from M_B^{bulge} with the standard expression for M_V^{bulge} (see eq. (3)) by assuming $M_B^{bulge} \simeq M_V^{bulge}$ for Seyfert 1s. We carefully checked

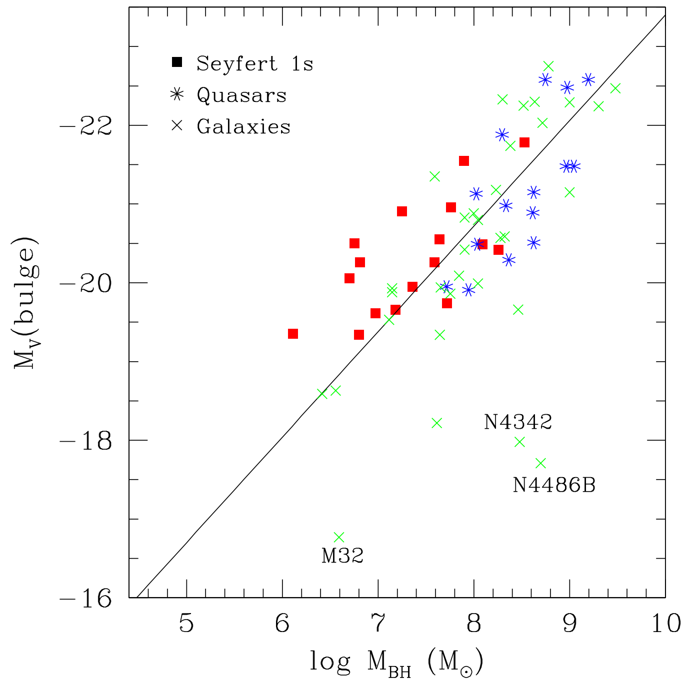

Fig. 4. Correlation between the V-band absolute bulge magnitudes and black hole masses for quasars, normal galaxies and Seyfert 1 galaxies with black hole masses only measured by reverberation mapping. The solid line represents the least χ^2 fit to all objects by considering typical measurement errors of both parameters.

these points and re-derived the absolute bulge V magnitude of 17 Seyfert 1 galaxies with SMBH masses measured by reverberation mapping (Wandel et al. 1999), using $H_0 = 80$kms^{-1}Mpc^{-1} and assuming the bulge B-V color being nearly the same as the B-V color of the whole galaxy. The M_V^{bulge}-M_{BH} relation of 17 Seyfert 1 galaxies, as compared with those for 15 quasars (Laor 1998, 2001) and 30 nearby galaxies with M_{BH} measured by stellar dynamics (Gebhardt et al. 2000a), is shown in Figure 4. Allocating the 'typical' uncertainties of M_V^{bulge} and M_{BH} as we did above, the least χ^2 fit for 62 objects gives,

$$M_V^{bulge} = -10.00 \pm 0.96 - (1.34 \pm 0.12)\log(M_{BH}/M_\odot). \quad (6)$$

Considering the errors in both parameters, we estimated the mean correlation coefficient as $\langle r_S \rangle = -0.63 \pm 0.06$. This result is consistent with that found above (see eq. (2)) and also indicates a nonlinear M_{BH}-M_{bulge} relation.

5.3. Nelson & Whittle's sample of Seyfert galaxies

In this section we explore the Seyfert sample in Nelson & Whittle (1995), where the measurements of nuclear velocity dispersions of about 70 Seyfert galaxies were reported. After excluding several LINERs and normal galaxies, we got 33 Seyfert 1s and 32 Seyfert 2s. We estimated the SMBH masses of these Seyfert galaxies using the M_{BH}-σ relation (eq. (1)). The *total* radio power at

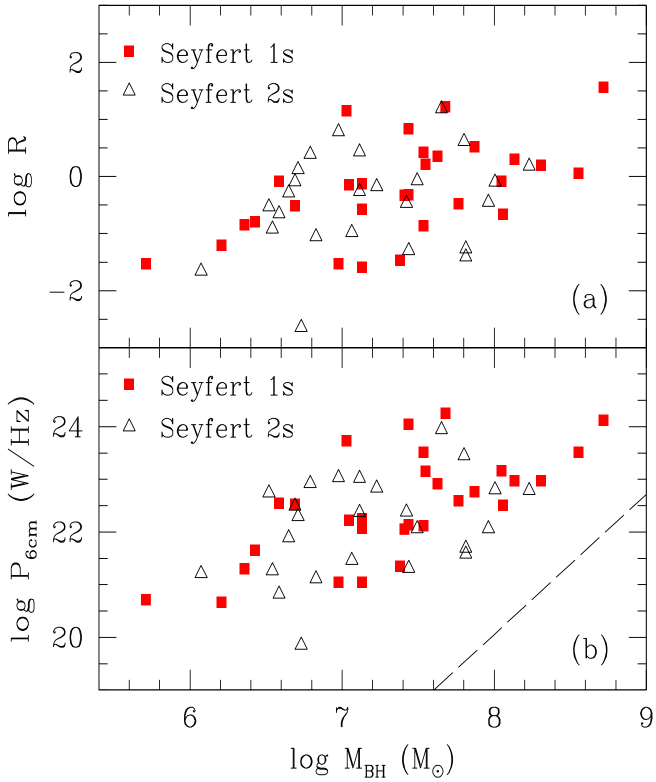

Fig. 5. The radio-loudness (a) and radio power (b) against the black hole masses for Seyfert galaxies in the sample of Nelson & Whittle (1995). The dashed line in (b) represents the tight correlation between total radio power and SMBH masses found by Franceschini et al. (1998) for nearby galaxies.

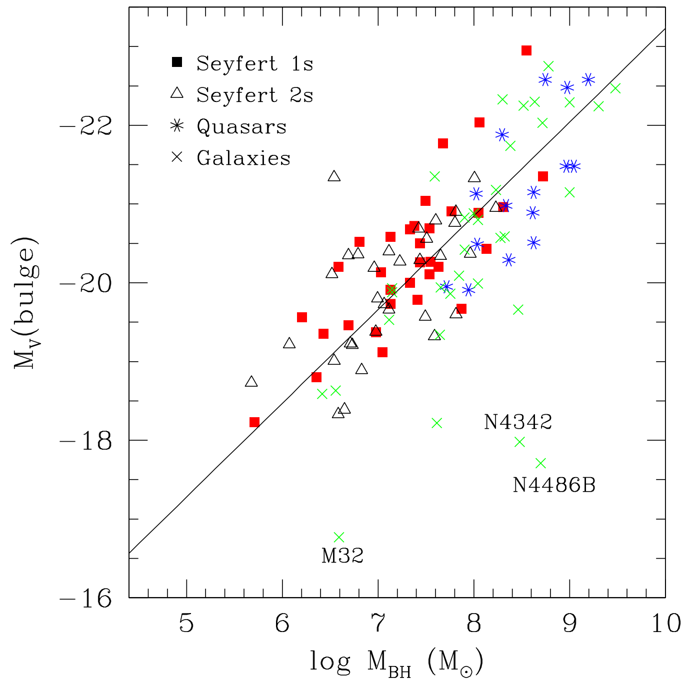

Fig. 6. Correlation of V-band absolute bulge magnitudes and black hole masses for quasars, normal galaxies and Seyfert galaxies in the sample of Nelson & Whittle (1995). The solid line represents the least χ^2 fit to all objects. The typical measurement errors of both parameters were considered.

5 GHz of them was calculated from the 1.4 GHz data in Nelson & Whittle (1995) by assuming $f_\nu \propto \nu^{-0.5}$ and $H_0 = 80\mathrm{kms^{-1}Mpc^{-1}}$. The radio-loudness was calculated by the 5 GHz radio luminosity and the B-band optical luminosity. The V-band bulge absolute magnitude was estimated from the B-band bulge absolute magnitude (adapted to $H_0 = 80\mathrm{kms^{-1}Mpc^{-1}}$) in Nelson & Whittle (1995) by assuming the B-V color of the bulge being the same as the total B-V color (taken from Verón-Cetty & Verón (2000)) of Seyfert galaxy.

The radio-loudness and total radio power against the SMBH masses for 29 Seyfert 1s and 25 Seyfert 2s with available radio data in the sample of Nelson & Whittle (1995) are plotted in Fig. 5. Now we see that most Seyfert galaxies seem to be radio quiet ($R < 10$) when we adopted the total radio and optical luminosities to calculate the radio-loudness. There is a weak tendency that Seyfert galaxies with larger radio-loudness have larger SMBH masses. A comparison with the result in Figure 2(a) indicates that the nuclear radio-loudness may be more fundamental and reflect the nature of central engine of Seyfert galaxies. From Figure 5(b) we see that there is a strong correlation between the total radio power and the SMBH mass, though the scatters are large. This confirms again the previous result that AGNs with larger radio power may host more massive SMBHs (Franceschini et al. 1998; McLure et al. 1999). However, as is shown in Figure 2, Seyfert galaxies depart significantly from the tight relation between the radio power and SMBH mass found for normal galaxies by Franceschini et al. (1998).

The relation between V-band bulge luminosities and SMBH masses for 33 Seyfert 1s and 32 Seyfert 2s in the sample of Nelson & Whittle (1995) is shown in Figure 6. It again indicates a significant universal relation between V-band bulge luminosities and SMBH masses for both Seyfert galaxies and quasars, as well as nearby galaxies. Adopting the 'typical' uncertainties of $M_V^{\rm bulge}$ and $M_{\rm BH}$ as we did above, the least χ^2 fit for 65 Seyfert galaxies, 15 quasars and 30 nearby galaxies gives,

$$M_V^{bulge} = -11.33 \pm 0.66 - (1.19 \pm 0.09)\log(\mathrm{M_{BH}/M_\odot}), (7)$$

The simple Spearman rank-order correlation coefficient is $r_S = -0.76$, which has a probability of $P_r = 1.1 \times 10^{-21}$ occuring by chance. Considering the errors in both parameters, we estimated the mean correlation coefficient as $\langle r_S \rangle = -0.61 \pm 0.04$. This result is also almost identical to what we found for the sample including 35 Seyfert galaxies. Therefore, the nonlinear $\mathrm{M_{BH}}$-$\mathrm{M_{bulge}}$ relation is confirmed by the substantially enlarged Seyfert sample.

5.4. Effects of larger systematic errors

A significant correlation between black hole mass and bulge luminosity was obtained above by considering the 'typical' errors of both parameters. These errors are mainly due to the measurement uncertainties of bulge magnitude and black hole mass. However, the systematic errors are probably substantially larger for both bulge magnitude and black hole mass. For example, if M_{BH} is determined by reverberation mapping, the systematic errors caused by the unknown BLR geometry, inclination may be as large as a factor of 3 or more (Krolik 2001). Using the M_{BH}-σ relation to estimate M_{BH} also has larger systematic errors due to the uncertainty of the slope of this relation. In addition, in deriving bulge magnitude from galaxy magnitude for Seyfert galaxies we adopted a statistical relation given by Simien & de Vaucouleurs (1986). The systematic errors caused by applying this relation are probably quite large and are difficult to estimate quantitatively.

In order to estimate the effects of possible larger systematic errors of black hole mass and bulge magnitude on our result, we adopted a bootstrap method by adding the systematic errors into the uncertainties of both parameters. Assuming the possible systematic errors for bulge absolute magnitude being 1 mag and those for black hole mass being 90% for all 35 Seyfert galaxies, 15 quasars and 30 normal galaxies, we obtained the average correlation coefficient using the bootstrap approach as being $\langle r_S \rangle = -0.40 \pm 0.09$, which indicates a moderately significant correlation. The minimum chi-square fit considering both measurement and systematic errors in both parameter gives, $M_V^{bulge} = -10.49 \pm 1.77 - (1.29 \pm 0.22) \log(M_{BH}/M_\odot)$. Comparing with the result we obtained in eq. (2), we found the slope of this relation does not change very much, though the uncertainty of the slope is doubled when the larger systematic errors are considered. The correlation coefficient also substantially decreases and its uncertainty increases accordingly. However, these changes are quite limited and have no significant effects on the result we have obtained.

6. Discussions

Our results obtained for a larger sample of Seyfert galaxies show that AGNs with a larger nuclear radio-loudness seem to have more massive black holes. This conclusion was obtained recently by Laor (2000) for nearby quasars and was supported by our study for Seyfert galaxies. Our results also strengthen the argument made by Ho & Peng (2001) that the majority of Seyfert 1s are essentially radio-loud AGNs. The total radio power of Seyfert galaxies increases with the black hole mass. At a given M_{BH}, quasars and Seyfert galaxies seem to have greater radio power than that of nearby galaxies. These difference may simply be due to the different level of nuclear activity for different kinds of galaxies. A recent study using the quasars from the FIRST Bright Quasar Survey found evidence for the dependence of radio-luminosity on accretion rate and SMBH mass (Lacy et al. 2001). This may help us to understand the origin of scatters in the relation between the radio power and SMBH mass. If we describe the nuclear activity of galaxies using the accretion rate $\dot{M}$, the difference of radio power at a given M_{BH} may show that quasars and Seyfert galaxies have larger $\dot{M}$ than nearby galaxies. This seems also consistent with the picture that the accretion process in these systems may be different (Fabian & Rees 1995; Di Matteo & Fabian 1996). Most likely ADAFs with very low accretion rate exist in the nuclei of nearby galaxies, while quasars and most AGNs probably host standard geometrically thin accretion disks with higher accretion rate. However, the radio emissions from radio-quiet AGNs and nearby galaxies are not well understood at present. Whether they are from ADAFs (Narayan et al. 1998) or from weak jets (Falcke & Biermann 1996, 1999) still remains uncertain. For radio-loud AGNs, the radio emissions are thought to be mainly from the jet and are probably related to the magnetic fields or black hole spin (Blandford & Payne 1982; Blandford & Znajek 1977). If the radio emissions correlate with the black hole mass and accretion rate, we need to explain the possible relations of these parameters with magnetic fields and black hole spin. However, no satisfactory theory can provide clear physics about these relations at present.

Using the sample including 37 Seyfert galaxies in two well-defined bright Seyfert samples, we studied the correlations of black hole masses with V-band bulge absolute magnitudes and bulge masses for active and normal galaxies. We find that the correlation between the black hole masses and the V-band absolute bulge magnitudes for Seyfert galaxies is almost consistent with those found for quasars and nearby galaxies. The combined sample of 37 Seyfert galaxies, 15 quasars and 30 nearby galaxies seem to follow a universal nonlinear relation between the black hole and bulge masses, $M_{BH} \propto M_{bulge}^{1.74 \pm 0.14}$, which is slightly steeper than that found recently by Laor (2001) for a sample including 9 Seyfert galaxies. Our results support the suggestion that the ratio of M_{BH} and M_{bulge} is not constant and galaxies with larger bulge luminosities or more massive SMBH probably have a larger M_{BH}/M_{bulge} ratio. Including 65 Seyfert galaxies in the larger sample of Nelson & Whittle (1995) led to almost the same result. In fact, the nonlinear relation between M_{BH} and M_{bulge} has been predicted by some theories and supported by some recent studies. For example, using a collapse model for black hole and bulge formation, Adams et al. (2001) predicted $M_{BH}/M_{bulge} \propto \sigma$, which gives $M_{BH}/M_{bulge} \propto M_{BH}^{1/4}$ if $M_{BH} \propto \sigma^4$. This states clearly that the ratio of black hole and bulge masses is not constant and can be larger for galaxies with more massive SMBHs. A similar result can be obtained by exploring the model of Wang, Biermann & Wandel (2000) who derived $M_{BH}/M_{bulge} \propto \sigma^{1.4}$. In addition, recent studies on narrow line Seyfert 1s showed that their mean M_{BH}/M_{bulge} ratio is significantly smaller than that for normal Seyfert galaxies (Mathur, Kuraszkiewicz,

& Czerny 2001), which is also consistent with our results because narrow-line Seyfert 1s probably have smaller M_{BH} than normal Seyfert galaxies (Boller, Brandt & Fink 1996).

Finally we would like to mention that the tight correlation between the black hole mass and bulge luminosity is not surprising and is actually expected from some existing well-known relations. From the M_{BH}-σ relation and Faber-Jackson relation between the bulge luminosity and σ (Faber & Jackson 1976), we certainly expect a relation between black hole mass and bulge luminosity. The detailed studies of this relation and the M_{BH}-M_{bulge} relation are necessary because these relations are probably more fundamental than the Faber-Jackson relation and are more closely related to the physics of black hole and galaxy formation. We noticed that our result on the M_{BH}-M_{bulge} relation implies a rather flatter L_{bulge}-σ relation than the Faber-Jackson relation. This seems to be supported by the finding of Nelson & Whittle (1996). However, the slope of the L_{bulge}-σ relation depends sensitively on the statistical method, sample selection and uncertainties of both parameters. In addition, in deriving the M_{BH}/M_{bulge} ratio, we adopted the same bulge mass-to-light ratio for Seyfert galaxies as for nearby galaxies obtained by Magorrian et al. (1998). Such a ratio may be smaller for Seyfert galaxies (Whittle 1992). Introducing a smaller bulge mass-to-light ratio may affect our results. We expect that further high quality observations on Seyfert galaxies, normal galaxies and quasars using the *Hubble Space Telescope* and larger ground-based telescopes could diminish the uncertainties in measuring the galactic bulge properties and central black hole masses of these objects. These efforts will undoubtedly help us to understand better the physics of formation and evolution of SMBHs and galaxies.

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